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Research paper

Improving the financial performance of solid forest fuel supply using a simple moisture and dry matter loss simulation and optimization

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ABSTRACT

We constructed a computation scheme that combines GIS, simulation and optimization techniques for assessing the moisture change, dry matter loss, transportation costs and net present value of solid forest fuel piles. This scheme was applied to predict the value of a stock composed of multiple piles, and to find the optimal feedstock allocation strategy, i.e. the selection of piles and the combustion time so that the total energy yield or the economic value of the energy production is maximized. According to the simulation, single Norway spruce energy wood piles reached their maximum energy content during July–August in boreal conditions in Finland. If a pile was created between January–September, the maximum energy content occurred in the same year, whereas for piles created between October–December, the maximum occurs in the summer of the following year. In the optimized combustion sequence, the piles generated in early Year 1 were combusted first. The main outcome of the study was that the simulation-optimization scheme can increase the gained net present value of the feedstock by 2.0%–6.4%, and the benefit increases with increasing heterogeneity of the feedstock. Forest fuel supplier can get considerable savings by applying the presented system to decide the combustion sequence of the existing feedstock. From practical point of view this is remarkable because the savings can be achieved without any investments only by arranging the transportation sequence. The presented computation system uses easily available input, can be modified to different condition, and can be run with standard IT-resources.

1. Introduction

Forest-based bioenergy contributes 26% of the total energy use in Finland. In 2016, heating and power plants consumed a total of 19.5 million solid cubic metres (134.64 PW) of solid wood fuels, representing an increase of 1.1 million cubic metres or 6% compared to the previous year, the highest on record so far. The main solid wood fuel used by the plants was forest chips, the consumption of which increased by one per cent year-on-year to 7.4 million cubic metres [1]. According to the National Energy and Climate Strategy for 2030 Finland aims to increase the use of forest chips in energy generation up to 13.5 $\mathrm{Mm^3\,yr^{-1}}$ by 2030. In EU, 209 $\mathrm{Mm^3}$ of forest biomass is used for energy production, which comprises 44% of all renewable energy production in EU [2,3]. The use of forest biomass for energy will continue and it will cover a remarkable part of European heat and electricity demand also in the future [4]. Forest chips consist of small sized whole trees or stems, logging residues and stumps. Typically the logging residues are stored as piles on site and subsequently at the roadside piles before transporting to regional combined heat and power (CHP) plants for combustion. Profitability of forest fuel use depends largely on smart control of logistics and quality of the feedstock.

The value for a biomass delivery e.g. truckload of wood chips is dominantly determined according to its net energy content, which increases with drying and decreases with wetting and dry matter loss. Net present value (*NPV*) of energy biomass storage such as piled energy wood at the roadside is decreased by transportation and chipping costs and positive rate of interest. In addition, microbial activity can cause substantial dry matter losses during storage. They can account 1–3% loss of dry material and thus energy content per month [5]. The losses have been found to be dependent on the season i.e. temperature and the time of the year, when the storage has been established.

Transportation cost crucially depends on the fuel moisture content, as the maximum transport load of dry fuel is limited by the truck container volume, whereas the total mass becomes a limiting factor for wet fuel [6]. Biomass in a pile is continuously subject to dry matter loss; therefore the timing of the transport and combustion play a key role

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when maximizing the pile value. Development of models to predict moisture content and dry matter losses of the energy wood storage has been subject to intensive research in recent years [7,8]. There is a mismatch between the timing of harvesting and consumption of wood fuels. As a result, biomass has to be stored over several months before it is delivered to the energy plant [9]. Models have enabled more precise timing of deliveries to maximize the energy content of the delivered biomass.

Discrete-event simulation has been applied to improve the capacity utilization of the transportation fleet over a calendar year. In addition, the information concerning the moisture content, size and location of stock piles was used to meet the demand variation of a CHP plant. It was find out that by delivering the large and dry piles near the end use facility during peak loads in winter, more even capacity utilization was achieved [10]. Also optimization techniques using moisture content modelling has been applied to optimally sequence the energy wood deliveries [11]. However, the impact of dry matter losses has not been considered in the previous studies. If there are simultaneously multiple piles available for the combustion, the sequence in which they are combusted becomes important, since each pile is in different phase of drying and dry matter loss. The number of possible sequences in which the piles can be combusted increases drastically: five piles can be combusted according to $5! = 120$ different sequences; but 15 piles have $15! = 1.3*10^{12}$ different sequences. Optimization techniques can be used to adjust the combustion sequence to improve the total profitability of the energy production.

Our aim was to compile a simple computation scheme that combines GIS, process simulation and optimization techniques for assessing the moisture change, dry matter loss, transportation costs and net present value of solid forest fuel piles in the feedstock; and to apply the scheme to solve a simple management problem. The problem was to predict the time of the maximum value of the stock, and to compose feedstock allocation strategies under the question: how should we choose the piles and the combustion time so that the total energy yield and the economic value of the stock is maximized? The question was assessed concerning the demand of the energy plant.

This paper presents an approach how to increase the economic value of solid forest fuel feedstock by deciding the combustion sequence of multiple piles. The computation scheme was compiled of simple, replaceable modules that describe the main features of pile drying and wetting, dry matter loss, energy content, and forming of transport and chipping costs. The modules can be substituted by detailed descriptions when considered necessary.

2. Materials and methods

2.1. Computation scheme

Our computation scheme combines GIS-analysis, simulation modelling, optimization techniques (Fig. 1), and existing information about physical properties of solid forest fuel and economics of transporting, chipping and combusting (Table 1). The initial moisture of the forest fuel, the rate of daily moisture change, and dry matter loss were based on empirical studies close to our study area. The results from these studies were fitted to time series depending on the day of the year to obtain continuous variables.

2.2. The study area and GIS

Our study area included three municipalities (Joensuu, Kontiolahti, Ilomantsi) in North-Karelia, Eastern Finland (Fig. 2). The computation feedstock was composed of $N_p = 15$ (Table 1) piles of solid forest fuel that were generated to random locations inside the study area using Qgis Random Point Tool. The shortest distance from each feedstock pile to the power plant along the public road network was computed using the Dijikstra algorithm in Qgis Network Analysis library [17]. The coordinates of the feedstock piles and the distances to the CHP-plant were saved into shape-file.

2.3. Supply of forest fuel and demand of energy

Solid forest fuel consists of residues left in the final harvest of a forest stand. In this study the piles consisted solely of logging residues from final fellings of Norway spruce stands (*Picea abies* (L.) Karsten). In the simulation, time of the solid forest fuel pile generation matters, because i) the initial moisture of the logging residues is higher in the autumn and winter than in spring and summer, and because ii) the logging residues tend to dry during spring and summer and to wet during autumn and winter. The harvests are more frequent during the winter than during the summer months [18]. To take into account the temporal variation in the pile properties, the simulation piles were compiled from regional monthly harvesting data in a following way: a sine curve was fitted to the time series of the harvesting data, then using the curve, a daily cumulative harvesting scheme was created and Julian day was presented as a function of cumulative harvest. Subsequently, the cumulative harvest was divided into equally spaced intervals (number of piles in the study, $N_p = 15$) and the Julian day for each pile generation was computed (Fig. 3).

Likewise, the energy consumption, and therefore the daily combustion rate, is unevenly distributed through the year, the maximum energy use being during the winter months [19]. Therefore, in our analysis, the time of pile combustion matters as well. Like in the harvesting computation, a sine curve was fitted to the energy consumption time series, and Julian day was described as a function of cumulative daily energy consumption. Again, the cumulative energy consumption was divided into $\mathrm{N_p}$ equally spaced intervals, and the Julian day for the combustion events was solved.

In the Simulation 1, the piles were generated during Year 1 beginning from January and combusted during Year 2 beginning from January (see Fig. 5). In order to study the performance of the optimization under different feedstock composition, we shifted the beginning of the simulation with monthly steps from January to December (Simulation Set).

2.4. Pile moisture content and dry matter loss

Initial moisture of the solid forest fuel is typically higher if a stand is harvested during the winter months than in those stands harvested during the summer months. A sine curve was fitted to the time series [19] to describe the initial moisture (W_{ini}) for a pile generated on any day of the year (Fig. 4). Using the familiar fitting procedure a sine model was constructed for Daily Moisture Change (*DMC*) of the solid forest fuel piles [11]. The *DMC* values, describing net average change of pile gravimetric moisture as a function of day of the year (Julian day), have been experimentally determined earlier for the same region as our study area. For each pile, we computed W_{ini} from the day of pile generation (t_0, Julian day) and the W_{ini}-model. The instantaneous moisture content (W_t) of a pile was calculated from the W_{ini} and the cumulative moisture change, which was obtained by integrating the *DMC* function from t_0 to t.

The biomass in the pile is continuously subject to dry matter loss caused by microbial decomposition. The dry biomass remaining in the pile at time t (M_t) in the pile was calculated from the mass in the previous time step (M_{t-1}), and exponential decay function (Eq. (1)), [21,22].

$$M_t = M_{t-1} \exp(-k_t dt) \tag{1}$$

Where k_t is the day-specific daily decay coefficient (day^{-1}) and dt is time step length in days. Since the dry matter loss is a result of microbial activity, the decay coefficient was assumed to be dependent on temperature according to Q_{10} function e.g. Refs. [23,24]: